

Fine detrending of raw Kepler and MOST photometric data of KIC 6950556 and HD 37633

Zdeněk Mikulášek¹, Ernst Paunzen¹, Miloslav Zejda¹, Evgenij Semenko²,
Klaus Bernhard³, Stefan Hümmerich³, Jia Zhang^{1,4}, Svetlana Hubrig⁵,
Rainer Kuschnig^{6,7}, Jan Janík¹, Miroslav Jagelka¹

¹ Department of Theoretical Physics and Astrophysics, Masaryk University,
Kotlářská 2, cz 611 37 Brno, Czech Republic

² Special Astrophysical Observatory of the RAS, Russia

³ Bundesdeutsche Arbeitsgemeinschaft für Veränderliche Sterne e.V. (BAV),
Berlin, Germany

⁴ National Astronomical Observatories/Yunnan Observatory, Chinese Academy of
Sciences, Kunming, China

⁵ Leibniz-Institut für Astrophysik Potsdam (AIP), Potsdam, Germany

⁶ University of Vienna, Institute for Astronomy, Vienna, Austria

⁷ Department of Physics and Astronomy, University of British Columbia,
Vancouver, Canada
mikulas@physics.muni.cz

(Submitted on xx.xx.xxxx; Accepted on xx.xx.xxxx)

Abstract. We present a simple phenomenological method for detrending of raw Kepler and MOST photometry, which is illustrated by means of photometric data processing of two periodically variable chemically peculiar stars, KIC 6950556 and HD 37633. In principle, this method may be applied to any type of periodically variable objects and satellite or ground based photometries. As a by product, we have identified KIC 6950556 as a magnetic chemically peculiar star with an ACV type variability.

Key words: data processing, Kepler and MOST photometry, chemically peculiar stars, stars individual: KIC 6950556, HD 37633

Introduction

Nowadays, the amazing accuracy of nearly continuous photometric observations made from space satellites enables us to study subtle details in the light variations of variable stars. However, raw space photometric data contain different systematic trends associated with the spacecraft, detector and environment rather than the target. To exploit maximum information hidden in satellite photometry, we need to eliminate all these trends as good as possible. We have developed a way of detrending raw photometry using appropriate phenomenological models of the real light curve modulated by instrumental effects. To display the efficiency of the method, we have processed raw photometric data of two strictly periodic CP stars with smooth light curves obtained by the Kepler and MOST satellites.

1. Kepler – KIC 6950556

KIC 6950556 (= 2MASS J19294376+4229306; 12.751 ± 0.024 mag) was classified by McNamara et al. (2012) as a B-type binary or a star whose light curve is dominated by rotation. Furthermore, it was preliminarily identified as an ellipsoidal (ELL) variable star candidate with a period of 1.5116 d by

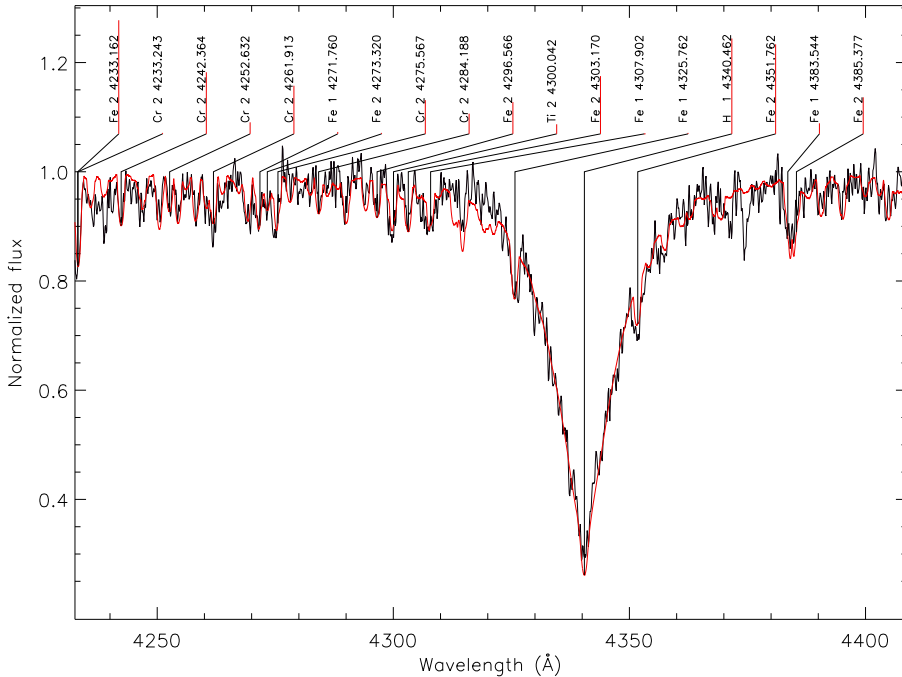


Fig. 1. A part of the spectrum of SiCr CP2 star KIC 6950556, fitted by the atmosphere model with an effective temperature of 11 000 K, $\log g = 4.0$, and enhanced abundances of chromium, iron, and silicon.

Balona et al. (2015). According to the double-wave light changes and the effective temperature, we also assumed ACV (α_2 CVn) variability. The classification of KIC 6950556 as a magnetic chemically peculiar star was subsequently confirmed by our analysis of two newly obtained spectra in the spectropolarimetric mode using the 6m telescope of Special Astrophysical Observatory of the Russian Academy of Science, Nizhnii Arkhyz (see Fig. 1).

Spectral analysis of spectrograms shows that KIC 6950556 is B8-9 V star with an effective temperature of $T_{\text{eff}} = 11\,000(700)$ K, $\log g = 3.5 - 4.0$, and a projected rotational velocity $V \sin i = 60(10)$ km s $^{-1}$. Assuming a typical radius of the stars with such parameters $R = 2.4 R_{\odot}$ (according to tables in Harmanec 1988) we can also estimate the inclination angle $i \doteq 50^{\circ}$. The observed spectrum is apparently peculiar due to strong overabundance of chromium, iron, silicon, and underabundance of helium and calcium in the stellar atmosphere. If overabundant elements are distributed unevenly on the surface of the rigidly rotating star, they should form photometrically contrasting spots causing light variability of the star.

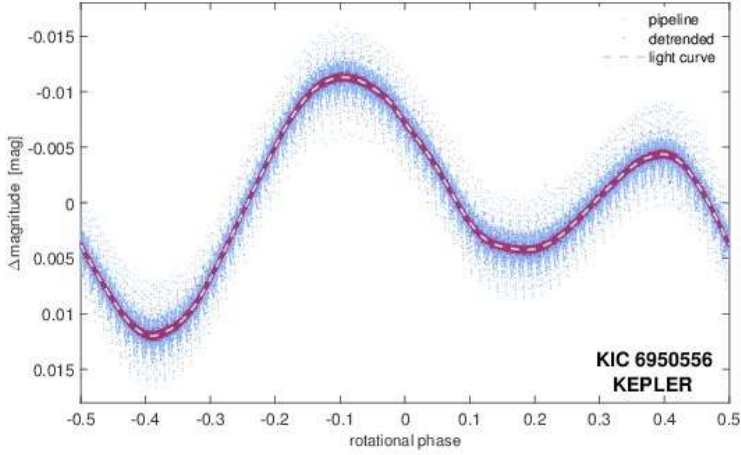


Fig. 2. Phased light curve of KIC 6950556, based on photometric data detrended by the Kepler pipeline (powder-blue dots) and data detrended by our code (magenta dots). The dashed grey line is a fit of the light variations by a harmonic polynomial of the 35-th order.

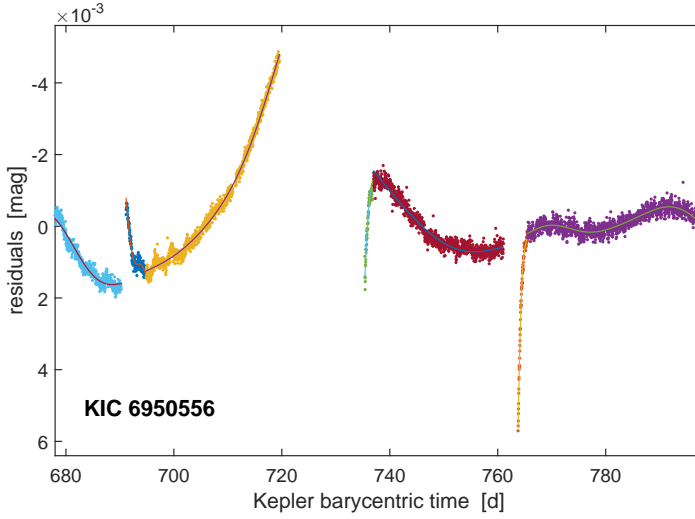


Fig. 3. Detail view of seven residual segments fitted by special function series.

The photometric analysis was based exclusively on raw Kepler data (Q0-Q17) which exhibit a scatter of 32 mmag as processed by the Kepler pipeline

(Jenkins et al. 2010). Such a preprocessed set of 64 793 individual observations of KIC 6950556 exhibits a scatter of 1.0 mmag – see Fig. 2. The detailed

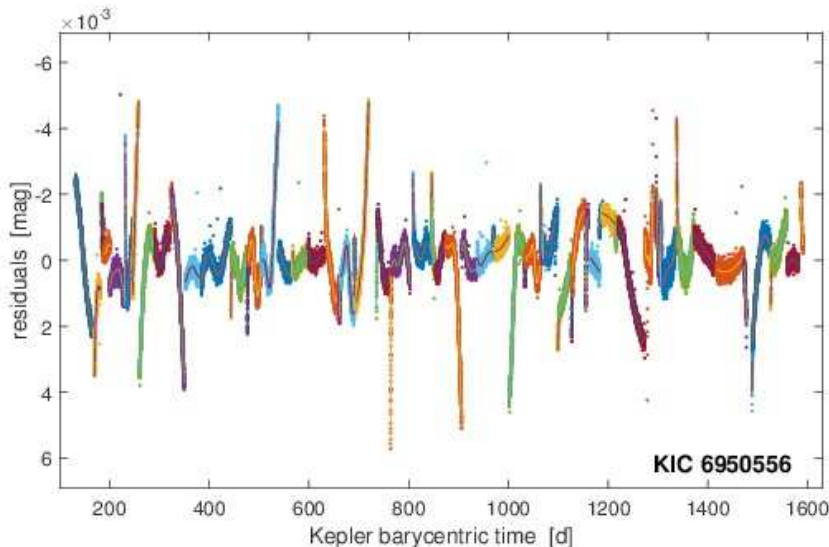


Fig. 4. Residuals fitted by 75 smooth lines.

analysis of the light residuals indicates a very strong correlation of adjacent points (see Fig. 3) which can be removed by fine detrending. Residuals were divided into 75 intervals of uneven lengths and fitted by series of special quasi-orthogonal functions (Mikulášek & Gráf 2005) of 0 to 7-th orders (see Fig. 4). After the detrending, which is described by 256 free parameters, we obtained a corrected light curve with a scatter of 0.13 mmag, which is close to the expected limit of accuracy of the Kepler satellite photometry. The detailed description of the mathematics of the detrending procedure will be published elsewhere.

The light curve itself was fitted by a harmonic polynomial of the 35-th order (see Fig. 2). The accuracy (5×10^{-7} mag) and reliability of the detrended light curve is sufficient for deriving the positions of photometric spots on the surface of the rotating star. The complex shape of the light curve with unequally high maxima in the double-wave (see e.g. Morris 1985) also do not support the classification of KIC 6950556 as an elliptical variable star or B-type binary (Balona et al. 2015; McNamara et al. 2012).

We also refined the period of the star to: $P = 1.511\,785\,08(4)$ d, which seems to be fairly constant: $\dot{P} = 1(2) \times 10^{-10}$. It should be noted that the accuracy of the period rate determination of 2×10^{-10} is high enough to reveal all presently known CP stars exhibiting variable periods (Mikulášek et al. 2014, 2015).

2. MOST – HD 37633

The MOST B9Vp CP2 star HD 37633 (= V1147 Ori) was identified as a variable star by North (1982). Later, North (1984) published its period $P = 1.5718$ d and light curves of the star in the Geneva system. Our photometric

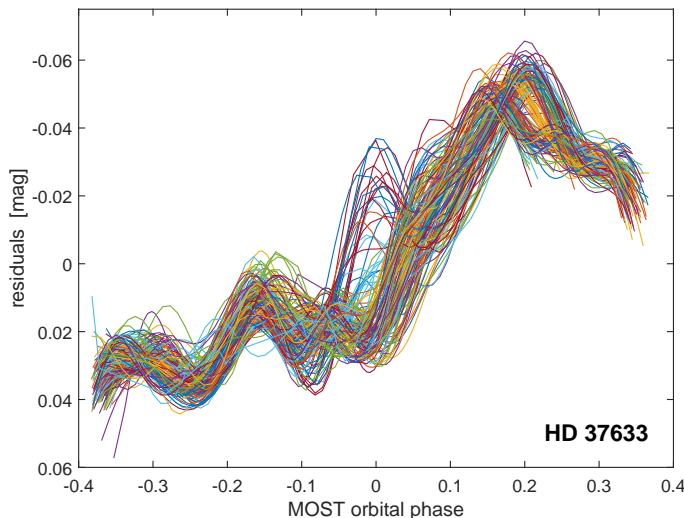


Fig. 5. Residuals plotted versus the MOST orbital phase. Each of the 146 MOST passages were fitted by its own curve.

analysis was based on 10 572 raw MOST measurements obtained during 10.5 d (6.7 photometric cycles). We fitted the raw measurements by a harmonic polynomial of the 5-th order using a robust regression suppressing the influence of outliers (Mikulášek et al. 2003). The residuals, having an amplitude of 0.1 mag, are strongly correlated with the phase of the orbital revolution of the MOST satellite (101.48 min); nevertheless each of the 146 passages differs from each other.

Consequently, we modelled the individual course of each observational interval using linear combination of 14 special functions mentioned above (see Fig. 5). Subtracting these trends, which are correlated with the MOST orbital period, we obtained detrended magnitudes defining the light curve with a scatter of 75 mmag (see Fig. 6). 207 measurements were deleted. The data filtered by the MOST pipeline (Hareter et al. 2008) have the same scatter as our detrended data, but the number of deleted measurements is larger: 497.

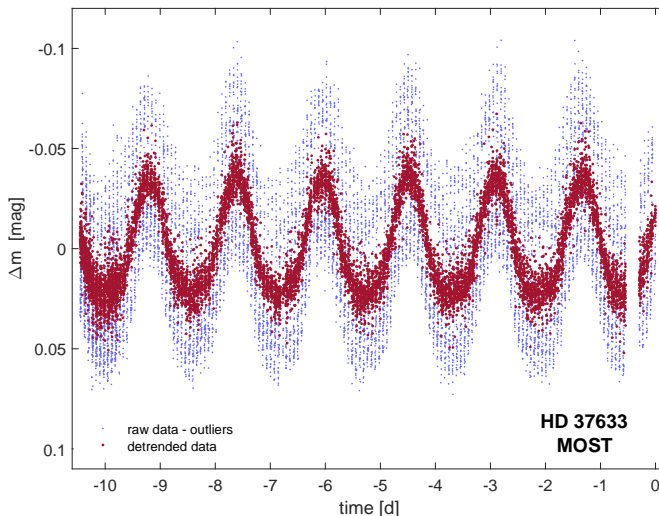


Fig. 6. Phased light curve of HD 37633 defined by its raw photometric data (powder-blue dots) and data detrended by our code (magenta dots).

3. Conclusions

We have shown that the proposed way of the phenomenological detrending of raw Kepler and MOST data is able to improve light curves of periodically variable stars considerably. The outlined method can be used also for the final processing of ground based (ASAS, Pan-STARRS, and SuperWASP) as well as satellite based (BRITE, CoRoT, and PLATO) data. The phenomenological detrending can be essentially applied to all variable objects whose periods and light curves are constant or regularly changing. That is valid for all rotators (CP stars, elliptical stars, spotted star, asteroids), eclipsing systems (binaries or stars transited by their planets), and several types of pulsators (RR Lyr stars, cepheids, δ Sct stars, and so on), among variable objects.

Simultaneously, we have revealed that the Kepler star KIC 6950556 is definitely a common CP2 star with an effective temperature of 11 000 K, $\log g = 4.0$, and enhanced abundances of chromium, iron, and silicon, rotating with a constant period of $P = 1.511\,785\,08(4)$ d. The observed light variability is then caused by the incidence of two or more photometric spots on its surface.

Acknowledgements

The work is partly based on data collected with the KEPLER and MOST satellites. The study is supported by the grants of Ministry of Education of the Czech Republic LH14300, grant of Masaryk University MUNI/A/1110/2014,

by the Czech Science Foundation grant no. GA13-10589S. This project is financed by the SoMoPro II programme (3SGA5916). The research leading to these results has acquired a financial grant from the People Programme (Marie Curie action) of the Seventh Framework Programme of EU according to the REA Grant Agreement No. 291782. The research is further co-financed by the South-Moravian Region. This work reflects only the author's views and the European Union is not liable for any use that may be made of the information contained therein.

Bibliography

- Balona L. A., Baran A. S., Daszyńska-Daszkiewicz J., De Cat P., 2015, Mon. Not. R. Astron. Soc., 451, 1445
- Hareter M., Reegen P., Kuschnig R., et al., 2008, Asteroseismology, 156, 48
- Harmanec P., 1988, Bull. Astron. Inst. Czechosl., 39, 329
- Jenkins J. M., Caldwell D. A., Chandrasekaran H., et al., 2010, ApJ Letters, 713, 87
- McNamara B. J., Jackiewicz J., McKeever J., 2012, AJ, 143, 101
- Mikulášek Z., Gráf T., 2005, Contr. Astron. Obs. Skalnaté Pleso, 35, 83
- Mikulášek Z., Krtička J., Janík J., et al., in Putting A Stars into Context, Proceedings of the conference held on June 3-7, 2013, Moscow, Russia. Eds.: G. Mathys, E. Griffin, O. Kochukhov, R. Monier, G. Wahlgren, Moscow: Publishing house "Pero", 2014, 270
- Mikulášek Z., Janík J., Krtička J., et al., 2015, ASPC 494, 189
- Mikulášek Z., Žižňovský J., Zverko J., Polosukhina N. S., 2003, Contr. Astron. Obs. Skalnaté Pleso, 33, 29
- Morris M. 1985, ApJ, 295, 143
- North P., 1982, IBVS, 2208
- North P., 1984, A&A Suppl. Ser. 55, 259